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Solar and Wind Power Estimation and Economic Load Dispatch Using Firefly Algorithm

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Abstract

In this paper, economic load dispatch problem is discussed and implemented with firefly algorithm optimization technique to obtain the best optimal solution for the fuel cost of generator. Moreover, we have included the renewable sources in ELD problem, by estimating generation of solar and wind power through probability density function including the underestimation cost and overestimation cost of wind and solar units. In this problem it is been assumed that the renewable source units are located near the load center; hence we are neglecting the transmission losses by renewable sources and considering them only for the coal fired units (thermal units). The problem is then executed on four test cases with and without inclusion of renewable sources along with different combinations of renewable sources and validated them with experimental approach**.**

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Keywords: Economic load dispatch; firefly algorithm; wind power; solar power; probability density function;

1. Introduction

Electricity is the greatest invention that has fastens the development rate worldwide. Presently, electricity is morally present all around us in all activities. With increasing population on one hand and advancing technologies

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on other hand have made world ravenous and voracious appetite for electricity. Various predictions were made that estimates the 1% growth in consumptions per year, but for developing countries this has increased to 5% per year[1]. With this increasing demand of fossil fuel consumption for electricity generation in addition to bounded stock of fossil fuel have conscripted many countries to go forward for friendly alternative sources for energy which are renewable to sustain in this increasing demand scenario.

Energy policies also play a vital role to reduce the global energy crisis availability. This problem of energy crisis has received much attention from the utility companies and marked as most important operational needs. Conventionally, the economic load dispatch problem was solved with using the various methods viz. lambda iteration method, gradient search etc. to reduce the operating cost by a suitable constraints of power to be produced by different generating units or power plants. Many researchers have been done to extract power from renewable sources of energy viz. solar and wind. Moreover, these sources of energies are clean, renewable and are used where they are and their decentralized nature is well suited to the state of scattered areas of low population density. Consequently, they can contribute to environmental protection, reduce the emission of greenhouse gases, particularly successful CO_2 reduction, and to combat global warming, be considered as a future alternative to conventional energy , increased energy independence and preservation of raw materials. Our work revolves on two axes, firstly the wind and solar power estimation through probability density function and secondly, optimization of economic load dispatch problem using firefly algorithm. The management of optimal power extracted by conventional power plants is collaborated with the solar and wind farms by an improved natured inspired firefly algorithm (FFA).Simulation was performed on various test cases for thermal power plant with and without of renewable farms which proves the efficiency of this method, confirming the capacity of solving the economic load dispatch problem with the renewable energy.

Nomenclature

ELD	Economic Load Dispatch
FFA	Firefly Algorithm
WECS	Wind Energy Conversion System
PV	Photo Voltaic
pdf	Probability Density Function

2. Economic Load Dispatch

Economic Load Dispatch is the allocation of the load demand to the generating units in such a way that it is fully satisfied in the most economical way. In a typical power system, several generators are implemented to provide enough total output to satisfy a given total consumer demand. Each of these generating units usually has a unique cost-per-hour characteristic for its output operating range. In case of a nuclear power plant station has incremental operating cost for fuel and maintenance; and fixed costs associated with the station itself that can be quite considerable. When the transmission losses are considered then it is more complicated for the utilities to account. The equivalent cost of the generator includes mainly the fuel cost, labour cost and maintenance cost etc. The output power of fossil fuel plants is increased sequentially by opening of the steam valve to the turbines inlet. The quadratic fuel cost function can be given as[6]:

$$F(P_{gi}) = a_i P_{gi}^2 + b_i P_{gi} + c_i \quad Rs/hr \tag{1}$$

where, the $a_i, b_i and c_i$ are the generator constant coefficients. This fuel cost increases with the increase in the energy production i.e. electrical output power from the generator. We can broadly classify system constraints into two categories- equality constraints and inequality constraints.

2.1 Equality constraint: The cost function is not affected by the reactive power demand, so the full attention is given to the real power balance in the system. The balance equation of power is thus given by:

$$P_d = \sum_{i=1}^{N} P_{gi} \quad (2)$$

In the above equation transmission losses are not included, but the transmission losses are included in ELD problem then above equation 2 will get slightly modified as:

$$P_d + P_L = \sum_{i=1}^{N} P_{gi} \quad (3)$$

where, P_L is the transmission losses and P_d is the net load demand. Moreover the transmission loss can be calculated as,

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N} P_{gi}B_{ij}P_{gj} + \sum_{i=1}^{N} P_{gi}\, B_{0i} + B_{00} \quad (4)$$

where, the $B_{ij}, B_{0i}\ and\ B_{00}$ are the B-coefficients.

2.2 Inequality constraints: The inequality constraints can be further classified into generator and transmission loss constraints. These constraints can be described as :

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \quad (5)$$

$$Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max} \quad (6)$$

$$P_L > 0 \quad (7)$$

where, $P_{gi}^{min}\ and\ P_{gi}^{max}$ are the minimum and maximum real power generation limits of i^{th} unit respectively. Similarly, $Q_{gi}^{min}\ and\ Q_{gi}^{max}$ are the minimum and maximum reactive power generation limits of i^{th} unit respectively[6].

The renewable sources of energy are present in abundant quantity in nature like as solar energy, ocean energy, geothermal energy, biomass, wind energy, tidal energy etc.[5] These energy sources can be converted into various other form of useful energy, like electrical energy, mechanical energy, thermal energy, chemical energy etc. Mostly the electrical energy is the major demanded energy in today's world. So far, economic load dispatching with the conventional power sources, such as thermal, hydro, diesel and nuclear have been carried out, but due to the increasing demand of the power and also reducing conventional sources of energy, we need to rely on the renewable sources for power generation. The unit commitment along with these renewable sources, like wind, solar, bio-fuel, geothermal, etc., is also an important point of discussion. We majorly use wind power generation in the economic load dispatch problem due to large availability of the wind period in comparison to solar energy availability period. Also there is a vast scope of the solar power generation in India due to the high solar irradiance index. Presently many projects are already in progress of solar power generation in Gujrat, Rajasthan and other states of the country.

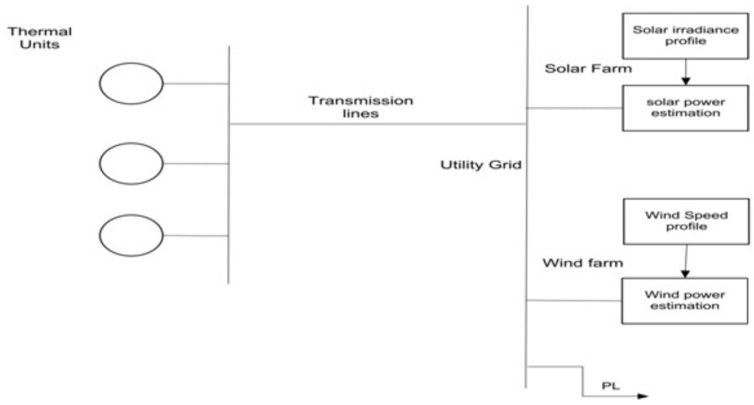

Figure 1. Hybrid Model of the PVS, WECS and FFS

The problem of economic load dispatch with the inclusion of the renewable power sources will reduce the load of generation on the thermal units and other fossil fuel units. Here in this paper we are including Photo Voltaic System (PVS) and Wind Energy Conversion System (WECS) in consortium with thermal power generation units. Adding factor of overestimation and underestimation of available wind power and solar power in power estimation section. The hybrid system with PVS, WECS and Fossil fired system (FFS) is thus shown in the figure 1.

3. Firefly algorithm

In 2007, Xin–She Yang developed a natured inspired algorithm based on the flashing behaviour of the fireflies. The flashing signifies the signal to attract other fireflies, where flashing of light or light intensity which helped the fireflies to move to brighter and more attractive locations are associated with the objective function to achieve optimal solution[9].

3.1 Biological association: Today more than 2000 species exists and the flashings of the fireflies can be seen in the summer sky in the tropical and temperate regions with warm weather and most active in the nights. These fireflies produce the short rhythmic patterns of flashing lights to attract their partners and these patterns of flashes are unique in species to species trough a bioluminescence process. However the flashing lights obey certain physical rules, the light intensity I decrease with the increase of distance r, i.e. $I \; \alpha \; 1/r^2$. Also the flashing is produced for communication purpose among each other and to attract prey, but still the flashing behaviour is a topic of discussion among scientists.

3.2 Idealized Rules for Firefly Algorithm: Three idealized rules are defined to characterize firefly.

First, All fireflies are unisex and they move towards the more attractive and brighter one irrespective of their sex.

Second, the level of attraction of firefly is proportional to brightness which reduces with the increase in the distance between two fireflies since air absorbs the light.

Third, the brightness or light intensity is determined by the value of the objective function of a given problem and it is proportional to the light intensity for a maximization problem[8].

3.3 Characteristics of firefly algorithm: The designing of firefly algorithm can formalize on two important issues- the variation of the light intensity and the attractiveness.

*3.3.1 Attractiveness :*In the FA the attractiveness follows a monotonically decreasing function given by,

$$\beta(r) = \beta_0^* exp\,(-\gamma r^m), \; with \; m \geq 1 \tag{8}$$

3.3.2 Distance: The Cartesian function is used to define the distance between any two fireflies i and j at position x_i and x_j respectively which is as follows:

$$r_{ij} = \left\|x_i - x_j\right\| = \sqrt{\sum_{k=1}^{d}(x_{i,k} - x_{j,k})^2} \tag{9}$$

Where $x_{i,k}$ is the kth component of the spatial coordination x_i of the ith firefly and d is the distance we have, i.e. d=2, we have

$$r_{ij} = \sqrt{(\,x_i - x_j)^2 + (\,y_i - y_j)^2} \tag{10}$$

3.3.3 Movement: The movement of the firefly i which is attracted by the firefly j is given by the following equation:

$$\mathrm{x_i = x_i + \beta_0 * exp(-\gamma r_{ij}^2) * (x_i - x_j) + \alpha * (rand - 0.5)} \tag{11}$$

where the first term is the current position of a firefly, the second term defines a firefly's attractiveness to light intensity seen by the adjacent firefly and the third term is for the random movement of a firefly if no brighter firefly is left. Random number generator (rand) which is uniformly distributed over the space [0, 1] and α is the randomization parameter. Now when $\gamma \rightarrow 0$ then attractiveness becomes $\beta = \beta_0$ i.e. the attractiveness is constant at every point in space, which is the special case of the particle swarm optimization (PSO). When$\gamma \rightarrow \infty$, the second term gets eliminated from equation (11) and the firefly movement becomes a random search method or random walk, which is the parallel version of the simulated annealing[4].

4. Problem Formulation

In this section we are going to discuss problem discussed in previous sections on four test cases which are as follows:

i. Economic load dispatch of 3 thermal units
ii. Economic load dispatch of 3 thermal units and 2 WECS systems.
iii. Economic load dispatch of 3 thermal units and 2 PV systems.
iv. Economic load dispatch of 3 thermal units and 1 PV and 1 WECS system.

4.1 Economic Load dispatch without Renewable Sources

The objective function for solving ELD problem without the inclusion of renewable sources can be described as:

$$F_T = F_1 + F_2 + \dots\dots\dots + F_N$$

This objective function can be also described by equation 12, this objective function is to be minimized for the best optimal values of the generation cost of the connected generator units to the system[2].

$$MIN\ F_T = \sum_{i=1}^{N} F_i(P_{gi}) \tag{12}$$

Subjected to,

$$P_d + P_L = \sum_{i=1}^{N} P_{gi} \tag{13}$$

where, $P_L$is the transmission losses and P_d is the total load demanded. Also, generator constraints and transmission line constraints are considered as follows.

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max} \tag{14}$$

$$P_L > 0 \tag{15}$$

4.2 Economic load dispatch with Renewable Sources:-

Both renewable energy systems are highly dependent on weather conditions and geographical locations. Probability based techniques can be used to define the variations in speed and solar irradiance distribution, thereby determining the performance and the feasibility of solar and wind power. Weibull probability density function (pdf) is used to estimate the wind speed and power.[7]

4.2.1 Wind and Solar Power Estimation:-

4.2.1.1 *Hourly wind speed and wind power output modelling:*

The Weibull's pdf is used for the wind speed estimation, the probability of wind speed being v during any time interval can be stated as:

$$f_v(v) = \frac{s_h}{s_c}\left(\frac{v}{s_c}\right)^{s_h-1} exp\left[-\left(\frac{v}{s_c}\right)^{s_h}\right], \quad for\ 0 < v < \infty \tag{16}$$

where $f_v(v)$ is the distribution probability of the wind speed (v), s_c and s_h are the scale and the shape parameter respectively. v is the annual average speed, v_m is the mean wind speed and σ is the mode speed which is speed of wind most of time. These parameters are calculated by the mean and standard deviation as follows:

$$s_h = (\frac{\sigma}{vm})^{-1.086} \tag{17}$$

$$s_c = \frac{vm}{\Gamma(1+\left(1/s_h\right))} \tag{18}$$

Furthermore the pdf of wind power can be formulated as:

$$f_{pw}(W_p) = \begin{cases} \left(\frac{s_h\, v_i\, l}{s_c}\right)\left(\frac{(1+\rho l)v_i}{s_c}\right)^{s_h\text{-}1} exp\left(-\left(\frac{(1+\rho l)v_i}{s_c}\right)^{s_h}\right) & ;\ for\ 0<v<v_r \quad (19) \\ 1\text{-}exp\left[-(\frac{v_r}{s_c})^{s_h}\right] + exp\left[-(\frac{v_0}{s_c})^{s_h}\right] & ;for\ v=0 \quad (20) \\ exp\left[-(\frac{v_r}{s_c})^{s_h}\right] \text{-}\ exp\left[-(\frac{v_0}{s_c})^{s_h}\right] & ;for\ v=v_r \quad (21) \end{cases}$$

Therefore, the wind turbine generated power at different velocities is calculated as:

$$W_p = \begin{cases} 0 & for\ v < v_i\ and\ v > v_0 \quad (22) \\ W_{pt}\left(\frac{v-v_i}{v_r - v_i}\right) & for\ v_i \le v \le v_r \quad (23) \\ W_{pr} & for\ v_r \le v \le v_0 \quad (24) \end{cases}$$

where the $\rho = {}^{v}/{}_{v_r}$ and $l = {}^{(v_r - v_i)}/{}_{v_i}$, v_i, v_r , and v_0 are the cut in, rated and the cut out speed for WECS system.

4.2.1.1 Hourly solar irradiance and PV output modelling

The solar radiation that reaches on the earth depends on the geographical location and weather conditions of the area. Moreover the cloudiness factor affects the difference of values measured outside and inside the atmosphere horizon

Here we are considering the clearness index pdf to model the hourly solar irradiance. The hourly clearness index (k_t) can be stated as the ratio of the irradiance on a horizontal plane I_t (kW/m^2) to the extraterrestrial total solar irradiance I_0 (kW/m^2). And can be calculated as:

$$k_t = \frac{I_t}{I_0} \tag{25}$$

$$f_{kt}(k_t) = \emptyset \left(1\text{-}\left(\frac{k_t}{k_{tu}}\right)\right) exp\,(\mu\, kt) \tag{26}$$

Where $\emptyset$ andμ are the maximum value and mean value of clearness index respectively and were calculated as,

$$\emptyset = \frac{\mu^2 k_{tu}}{(exp(\mu\, k_{tu}) - 1 - (\mu\, k_{tu})))} \tag{27}$$

$$\mu = ((2\varepsilon - 17.519\,)\, exp(1.3118\varepsilon) - 1062\, exp(-5.0426\varepsilon)))/((k_{tu})) \tag{28}$$

$$\varepsilon = \frac{k_{tu}}{k_{tu} - k_{tm}} \tag{29}$$

Now when the λ is determined corresponding value of c can be calculated from eq. 3.8. After this the solar irradiance can be calculated as ,

$$I_\beta = [J k_t - J' k_t^2] \tag{30}$$

where T and T' depends on inclination angle , ground reflectance, latitude, hour angle, sunset hour angle.

$$J = \left[\left(R_b + \rho\, \frac{1-cos\beta}{2}\right) + \left(\frac{1+cos\beta}{2} - R_b\right)p\right] I_0 \tag{31}$$

$$J' = \left(\frac{1+\cos\beta}{2} - R_b\right) q I_0 \tag{32}$$

where β is the inclination angel, R_b is the ratio of the beam radiation on a tilted surface to the horizontal surface, ρ is the reflectance of the ground and p and q are the constants.

$$k = p - qk_t \tag{33}$$

Now the sign of J and J' will decide the probability density function for solar power that has four different expressions but only two of them have the physical significance given as follows:

if J > 0 and J' < 0;

$$f_{pv}(W_{pv}) = \begin{cases} \frac{c(k_{tu}-0.5\,(\tau+\tau'))}{k_{tu}A_c\eta T'\tau'} exp\left(\frac{\lambda(\tau+\tau')}{2}\right) & if\, P_{pv} \epsilon\, [\,0, P_{pv}(k_{tu}) \\ 0; & \end{cases} \tag{34}$$

if J > 0 and J' > 0 then ,

$$f_{pv}(W_{pv}) = \begin{cases} \frac{c(k_{tu}-0.5\,(\alpha-\alpha'))}{k_{tu}A_c\eta T'\alpha'} exp\left(\frac{\lambda(\alpha-\alpha')}{2}\right) & if\, P_{pv} \epsilon\, [\,0, P_{pv}(k_{tu})] \\ 0; & \end{cases} \tag{35}$$

where, the α and α′ are given by,

$$\alpha = \frac{T}{T'} \text{ and } \alpha' = -\sqrt{\alpha^2 - \frac{4P_{pv}}{\eta\, T' A_c}} \tag{36}$$

4.3 *Objective Function for ELD including Renewable sources*

The objective function of the new ELD problem with the renewable sources can be described as,

$$min\ F_t = \sum_{i=1}^{N} OC(P_{gi}) + \sum_{j=1}^{M} OC(P_{wj}) + \sum_{k=1}^{S} OC(P_{pvk}) \tag{37}$$

Subjected to,

$$P_D + P_L - \sum_{i=1}^{N} P_{gi} - \sum_{j=1}^{M} P_{wj} - \sum_{k=1}^{S} P_{pvk} = 0 \tag{38}$$

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \tag{39}$$

$$0 \le P_{wj} \le P_{wrj}^{max} \tag{40}$$

$$0 \le P_{pvk} \le P_{pvrk}^{max} \tag{41}$$

First Term of equation 37 is operating cost of i^{th} thermal unit$OC(P_{gi})$, similarly second and third term are the operating cost of the wind farm $OC(P_{wj})$ and PV system$OC(P_{pvk})$. Also, P_{gi}^{min} and P_{gi}^{max} are the minimum and maximum real power generation limits of the i^{th} thermal generating unit, P_{wj} and P_{wrj} are the scheduled and rated power generation of the j^{th} wind farms, similarly P_{pvk} and P_{pvrk} are the scheduled and the rated power generation of the k^{th} solar system.

The operating cost of the wind farm is the sum of the three components: first part is the weighted cost function based on the speed of the wind, second part is the penalty cost for not using the available power of wind and the third part is the penalty cost on the reserves which is due to that the actual wind power is less than scheduled wind power. The combination of the operating costs can be described as,

$$\sum OC(Pwj) = \sum_{j=1}^{M} C_{wj}(P_{wj}) + \sum_{j=1}^{M} C_{p,wj}(P_{wj,av} - P_{wj}) + \sum_{j=1}^{M} C_{r,wj}(P_{wj} - P_{wj,av}) \tag{42}$$

Where,

$$C_{wj}(P_{wj}) = c_{wj} f_{pw}(P_w) P_{wj} \tag{43}$$

$$C_{p,wj}(P_{wj,av} - P_{wj}) = k_{p,wj}(P_{wj,av} - P_{wj}) \tag{44}$$

$$C_{r,wj}(P_{wj} - P_{wj,av}) = k_{r,wj}(P_{wj} - P_{wj,av}) \tag{45}$$

C_{wj} is the direct cost coefficient for the j^{th} wind unit, $f_{pw}(P_w)$ is the pdf of the wind from the eq. 19, 20 and 21. $k_{p,wj}$ and $k_{r,wj}$ are the penalty cost coefficients of underestimation and reserve cost coefficient of overestimation of the available wind power and $P_{wj,av}$ is the available wind power for the j^{th} unit.

Similarly, the operating cost of the solar farm is the sum of the three components: first part is the weighted cost function based on the solar irradiance, second part is the penalty cost for not using all the available PV generated power and the third part is the penalty cost on the reserves which is due to that the actual solar power is less than scheduled PV system generated power. Such system can be described by equation 46.

$$\sum OC(P_{pvk}) = \sum_{k=1}^{S} C_{pvk}(P_{pvk}) + \sum_{k=1}^{S} C_{p,pvk}(P_{pvk,av} - P_{pvk}) + \sum_{k=1}^{S} C_{r,pvk}(P_{pvk} - P_{pvk,av}) \quad (46)$$

Where,

$$C_{pvk}(P_{pvk}) = c_{pvk} f_{pvk}(P_{pv}) P_{pvk} \quad (47)$$

$$C_{p,pvk}(P_{pvk,av} - P_{pvk}) = k_{p,pvk}(P_{pvk,av} - P_{pvk}) \quad (48)$$

$$C_{r,pvk}(P_{pvk} - P_{pvk,av}) = k_{r,pvk}(P_{pvk} - P_{pvk,av}) \quad (49)$$

C_{pvk} is the direct cost coefficient for the k^{th} solar unit, $f_{pvk}(P_{pvk})$ is the pdf of the wind from the eq. 34 and 35 depending on the sign of the T and T`, $k_{p,pvk}$ and $k_{r,pvk}$ are the penalty cost coefficients of underestimation and reserve cost coefficient of overestimation of the available PV power and $P_{pvk,av}$ is the available PV generated power for the k^{th} unit. In our problem we have considered that the renewable power generators are situated near the load centre, so neglected the transmission losses due to them. Transmission losses only due to thermal generating units are considered [14].

5. Results and Discussions

After the three thermal generating units considered are having different characteristic. Their characteristic cost function is given below by following equations,

$$F1 = 0.00816\, P_{g1}^2 + 7.02 P_{g1} + 200 \quad Rs/hr$$
$$F2 = 0.00900 P_{g2}^2 + 6.35 P_{g2} + 180 \quad Rs/hr$$
$$F3 = 0.00782\, P_{g3}^2 + 6.97 P_{g3} + 140 \quad Rs/hr$$

The operating limits of the generator are different for each unit which is enlisted below:

P_i^{min} (MW)	P_i^{max} (MW)
10	85
10	80
10	70

Also, the transmission loss coefficients considered were,

$$B_{ij} = \begin{matrix} 0.000218 & 0.000093 & 0.000028 \\ 0.000093 & 0.000228 & 0.000017 \\ 0.000028 & 0.000017 & 0.000179 \end{matrix}$$

$$B_{0i} = 0.0003 \quad 0.0031 \quad 0.0015\ ; \qquad B_{00} = 0.030523$$

5.1 Case study-1: three thermal units system

In this case study we have considered only thermal generating units. The fuel cost and transmission loss obtained after solving problem with lambda iteration method and firefly algorithm are shown in the table 1and 2 respectively.

Table 1: Fuel cost obtained from lambda iteration method for test case 1.

Sr. no.	Load demand (MW)	Fuel cost FC(Rs/Hr)	Transmission loss(MW)	Elapsed Time(sec)
1	50	888.7431753	0.718523234	0.848719
2	100	1231.63755	1.486767959	0.502648
3	125	1422.159458	2.084005739	0.404189
4	150	1625.4586	2.813864755	0.438529
5	200	2022.155835	4.679717947	0.597678

Table 2: Fuel cost obtained from Firefly algorithm for test case 1

Sr. No.	Load demand (MW)	Fuel cost (Rs/hr)	Transmission loss (MW)	Elapsed Time (sec)
1	50	865.0531503	0.417351908	2.706780
2	100	1230.858158	1.349369266	1.42682
3	125	1421.561972	1.964774407	2.00838
4	150	1616.921725	2.721760653	2.360528
5	200	2022.791132	4.652667582	2.366778

In table no 1 and 2 as it can clearly see that the fuel cost obtained after optimizing by firefly algorithm is lower than that was obtained from lambda iteration method. The fuel cost versus various load demands curve and fuel cost per iteration curve for 125 MW load demand is been shown in figure 2 and 3 respectively.

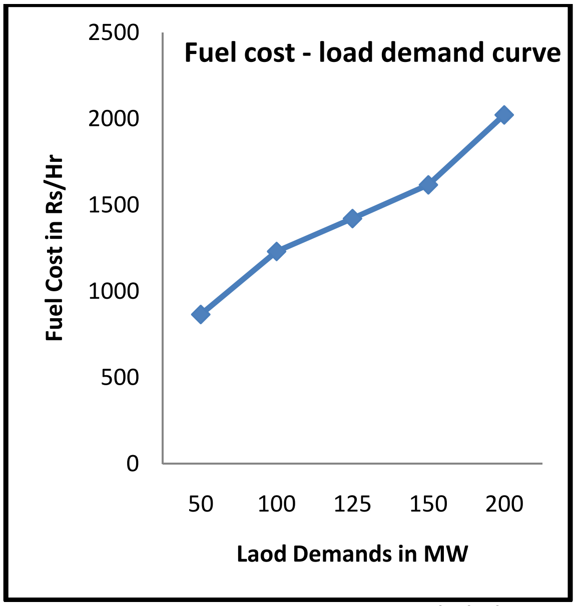

Figure 2: Fuel cost versus various load demands for firefly algorithm.

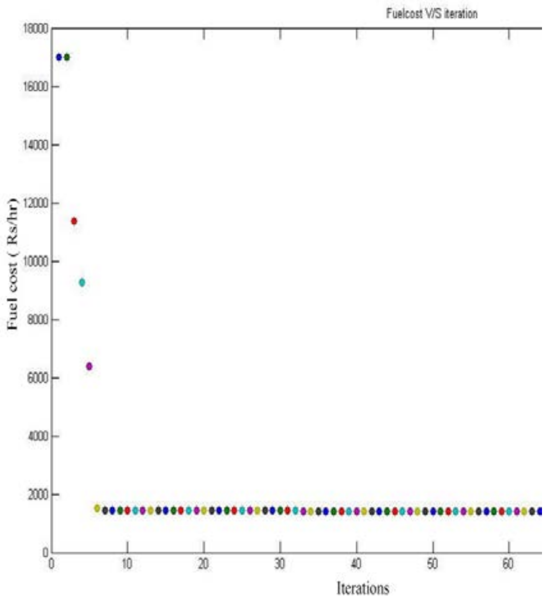

Figure 3: Fuel cost per iteration curve for 125 MW load demand.

5.2 Case study-2: economic load dispatch with 3 thermal units and 2 wind units using firefly algorithm

In this case study we have considered 3 thermal units and 2 wind farms each of 30 MW generation capacities. The direct cost coefficient, penalty cost coefficient and reserve cost coefficient for the wind power are 4.89Rs/KW, 17.280 Rs/KWh and 12.280 Rs/KWh respectivel[13]. The cut in speed cut out speed and the rated speed of the wind turbine units are 3.5 m/s, 25 m/s and 15 m/s respectively. The results evaluated are shown in table 3. The wind farms assumed to be located near the load, hence neglecting the transmission losses due to wind farm unit.

Figure 4 and 5 shows the fuel cost for various load demands and fuel cost per iteration for 200 MW load demand respectively.

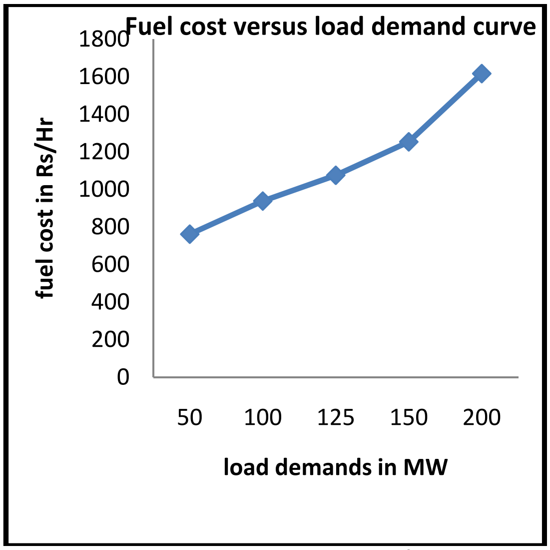

Figure 4: Fuel cost versus various load demands for case study 2.

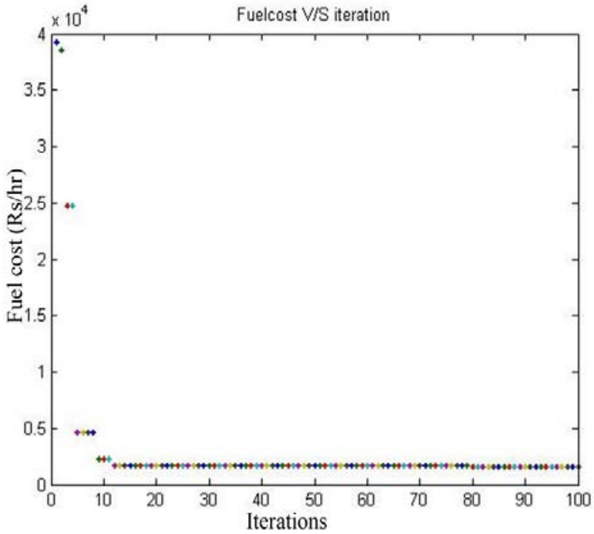

Figure 5: Fuel cost per iteration curve for 200MW load demand.

Table 3: Fuel cost obtained from Firefly algorithm for test case 2.

Sr. no.	Load demand (MW)	Fuel cost (Rs/Hr)	Transmission loss(MW)	Elapsed Time (sec)
1.	50	760.9097	0.48560685	2.08 560
2.	100	937.6889	0.8027887	2.137497
3.	125	1075.041	1.14066378	1.178443
4.	150	1253.03	1.674578933	1.238223
5.	200	1616.812	3.091949405	2.273712

5.3 Case study-3: economic load dispatch with 3 thermal units and 2 solar PV units using firefly algorithm:

In this case, we are considering the three thermal units with same cost functions and generator constraints as in the case study 2. And two solar farm units. The operating cost of the solar farm is given by equation 46, the direct cost coefficient of solar power, penalty cost coefficient and reserve cost coefficient for the solar power are 7.86 Rs/KW, 17.80Rs/KWh and 12.28 Rs/KWh respectively. The each PV unit capacity is 30 MW. The result with different load demand is shown in the Table 4. Figure 6 and 7 shows the fuel cost for various load demands and fuel cost per iteration for 200 MW load demand respectively.

Table 4: Fuel cost obtained from Firefly algorithm for test case 3.

Sr. no	Load demand (MW)	Fuel cost (Rs/Hr)	Transmission loss (MW)	Elapsed Time (sec)
1.	50	753.8376	0.204921526	2.380974
2.	100	931.8654	0.51105775	1.409495
3.	125	1081.215	0.86644477	1.415576
4.	150	1251.412	1.396535	1.667739
5.	200	1618.327	2.779728254	1.380076

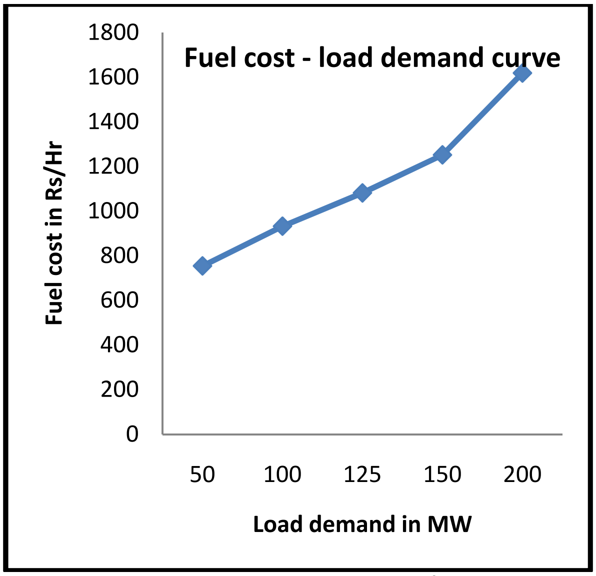

Figure 6: Fuel cost versus various load demands for case study 3.

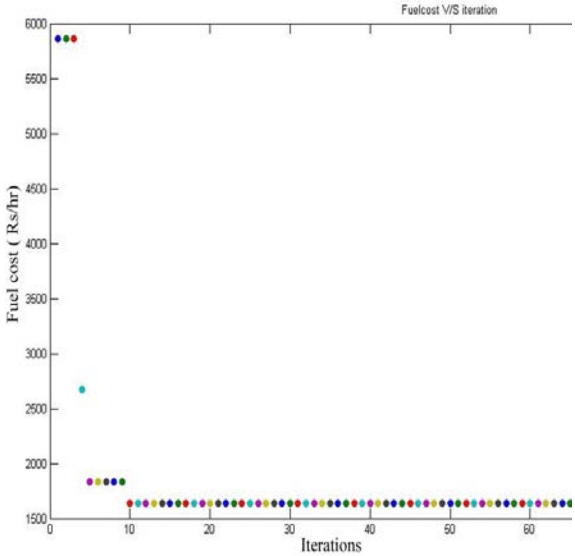

Figure 7: Fuel cost per iteration curve for 200MW load demand.

5.4 case study-4 economic load dispatch with 3 thermal units, 1 PV farm unit and 1 wind farm unit using firefly algorithm:

In this case study we have combined both the above cases study 2 and 3 discussed in the previous section, but here we are taking one unit each of 30 MW from both the renewable systems, i.e. one unit of solar farm and one unit of wind farm. The objective function of this case is described in the equation 37where the operating cost of the wind and solar units is shown in equation no. 42 and 46 respectively. The direct cost coefficient, penalty cost coefficient and the reserve cost coefficient of wind and solar are same as in the previous cases. Furthermore, the parameter values of the solar and wind units are kept same as that for the previous test case studies. The result is shown in the Table 5 for the different load demands. Figure 8 and 9 shows the fuel cost for various load demands and fuel cost per iteration for 200 MW load demand respectively.

Table 5: Fuel cost obtained from Firefly algorithm for test case4.

Sr. no.	Load demand (MW)	Fuel cost (Rs/Hr)	Transmission loss (MW)	Elapsed time (sec)
1.	50	755.9367	0.20966767	2.663824
2.	100	936.8157	0.52383516	2.428631
3.	125	1083.305	0.89684504	1.569667
4.	150	1252.756	1.44612158	1.388910
5.	200	1607.551	2.798475	1.392367

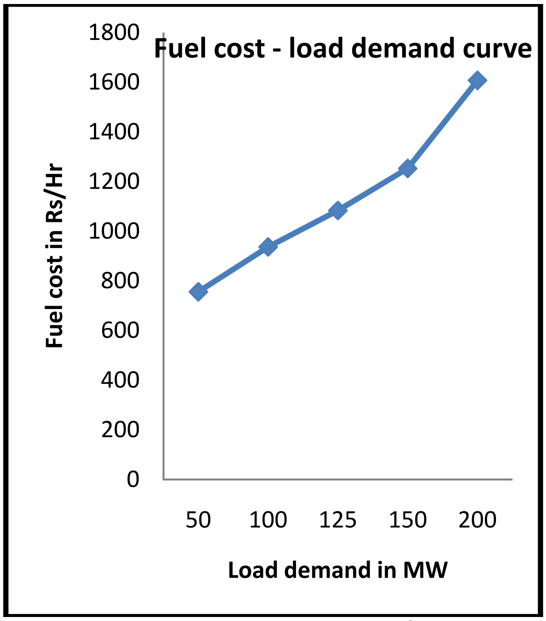

Figure 8: Fuel cost versus various load demands for case study 4.

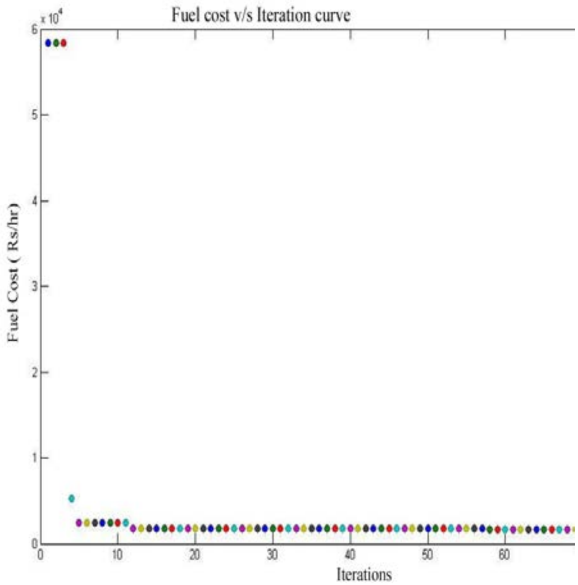

Figure 9: Fuel cost per iteration curve for 200MW load demand

6. Conclusion

With the inclusion of renewable sources of energy in the problem, the dispatching of load demand was simulated and it was concluded that the fuel cost of the thermal generating units and transmission losses (due to power transfer from thermal units to load centre) both reduces. This was due to the sharing of load by the renewable sources, the power generation by thermal units reduces and finally fuel cost reduces keeping the energy balance and other constraints within limits. A proper estimation of solar and wind probability density function should be made to determine actual probability of wind and solar power generation. The penalty cost and reserve cost coefficients however depend from state to state and country to country and their policies. These should be taken for the place for which the power estimation of wind and solar is to be made. Figure 10 depicts the variation of fuel cost for the various load demands in various case studies.

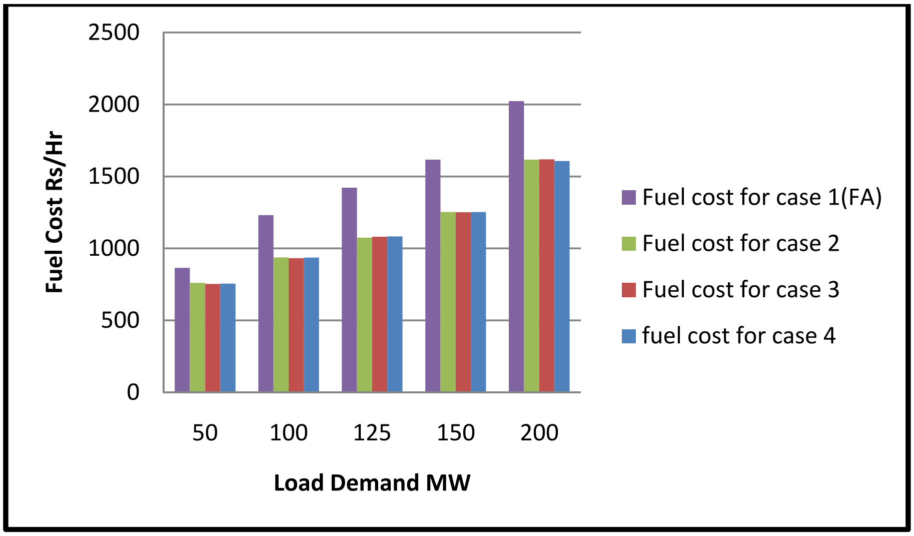

Figure 10: Comparison of fuel cost versus various load demands for all test case studies.

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